

EVALUATION OF UNSTAINED AND STAINED COTTON FABRIC BEFORE
AND AFTER ABRASION USING COLORED PHOTOMICROGRAPHS

by

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CHAPTER I

INTRODUCTION

Consumers and manufacturers are both interested in serviceable textile materials. Serviceability depends considerably on the abrasion resistance of the fabric. Fabrics may be subjected to various forms of abrasion, and the Standards for Textile Materials (1), published by the American Society for Testing Materials, cites several methods which are used by research laboratories. In the laboratory abrasion resistance depends on the specific method by which the fabric was abraded and on the technique by which the results were evaluated.

Abrasion occurs when one material is rubbed against another. It is a result of deformation due to compression, tension, shearing, bending, and cutting (21). The extent of abrasion influences the wearing qualities of a fabric. Kaswell (16) defines wear as "the ability of a fabric to withstand the effects of abrasion concomitant with stressing, straining, laundering, dry cleaning, pressing, creasing, etc." A fabric is serviceable if it performs the functions for which it was intended.

Though abrasion is recognized as a major factor in wear, little is known about the inherent abrasive behavior of textile fibers. The effect of abrasion on such physical properties as weight, breaking strength, thickness, or crease resistance has been given much attention. Microscopic analysis is needed to determine damage to abraded fabrics, yarns, and fibers, and to increase knowledge about the elements of fabric breakdown.

Considerable work has been done with various methods of mounting and staining longitudinal sections; however, much work needs to be done in developing a technique for studying cross sections of damaged fabrics. Stained longitudinal and cross sections can aid in the evaluation of damage. Photomicrographs of mounted fibers are valuable in a study of this nature. Recent studies, however, have reported dissatisfaction with the staining techniques that were used. Wahrenbrock (27) pointed out that colored photomicrographs would be helpful in analyzing stained cross sections.

The objectives of this study were: to develop a satisfactory technique of staining cotton fabric for cross-sectioning so that the degree of damage could be observed; to compare the cross sections of damaged cotton fabrics stained with different dyes; and to evaluate by use of colored photomicrographs the kind and degree of damage to cotton fabrics before and after varying degrees of abrasion.

CHAPTER II

REVIEW OF LITERATURE

The inherent mechanical properties of textile materials are related to the physical and chemical structure of the fiber. Hamburger (12) correlated abrasion resistance with the energy adsorption of mechanically conditioned fibers. For a fabric to resist abrasion it must be able to repeatedly absorb energy imparted to it by stress application. The fabric must be able to release the energy upon removal of the stress without the occurrence of failure. Fabrics are actually subjected in wear to many series of low stresses from which recovery is possible. It is the fabric's ability to perform after repeated stresses or deformations that influences abrasive resistance.

I. EFFECT OF ABRASION ON FABRICS, YARNS, AND FIBERS

Backer (2) stated that the three elements of abrasion are direct frictional wear, surface cutting, and fiber rupture or slippage. Stresses, which develop along the fiber axis from forces transverse to the axis, can result from surface friction or cutting and can cause fiber rupture or slippage. Frictional wear occurs most often when the surface of the abradant is smooth and the fibers are held firmly in the yarn structure. Surface cutting develops a complex stress pattern within the individual fiber. Backer (2) found that plucking could cause immediate rupture of the fiber at that point along the fiber length where maximum stress concentration was built up.

Kaswell (16) cited direct forces, impacts, and flexing or bending as the major sources of stress that a fabric may encounter. These stresses cause friction of fiber on fiber or yarn on yarn. Stoll (23) went even further and broke down the factors responsible for wear into approximately "30% plane abrasion, 20% edge and projection abrasion, 20% flexing and folding, 20% tear, and 10% other mechanical action." DeGrury et al. (8) listed frictional wear, cutting, and plucking as possible mechanisms of fiber breakdown during abrasion.

II. MICROSCOPIC EXAMINATION OF DAMAGE TO FIBERS

Longitudinal sections. McNally and McCord (19) concur with Backer (2) as to the mechanisms contributing to the physical destruction of fabrics, yarns, and fibers. Additionally, they point out three distinct types of damage noted in microscopic studies of damaged cotton fibers. The fiber may show evidence of fibrillation (a longitudinal disintegration of the fiber into a series of elements revealing the fibrillar structure). Secondly, damage to the cuticle of the fiber was noticed. This appeared to result from gentle abrasion which caused loosening, tearing, partial, or complete removal of the cuticle. Transverse cracking was also apparent. Considerable bending and flexing caused this to occur especially in a laminar structure (such as a cotton fiber) when stress is non-uniformly distributed.

Considerable work has been reported concerning mounting and staining techniques used to observe fiber breakdown with the microscope. Congo Red has been used successfully in staining cotton fibers in order

to observe damage. The Congo Red test described by Clegg (7) is based on: the different rates of diffusion of direct dyes into the exposed secondary cellulose and the cuticle of the cotton fibers after swelling in caustic soda; the behavior of the cotton fiber after swelling in regard to the constricting action of the cuticle; and the spiral splitting of the cuticle. The damaged areas of the fiber take up the color more readily and stain a bright red while the undamaged areas stain pink.

Bright (4) studied cotton hairs using the Congo Red test and found that the cut or weakened cuticle of the fiber appeared bruised. Many surface bruises and mechanical deep cuts were visible under the microscope. Clegg (7) used the same test procedure and noted the following damage: disturbance of the fiber arrangement within the yarns and damage and breakdown of the crowns of the warp yarns that predominated on the surface of the fabric. She attributed the fiber disarrangement to a general loosening of the fibrillar structure followed by a gradual disruption of the fibers which resulted in brush-like ends.

In a later microscopic investigation of cotton fibers from worn garments, Clegg (6) concluded that the breakdown in the yarn was due to the individual fibers. After staining with Congo Red, she noted protruding fiber ends, transverse markings, cracks, fibrillation, and bruising. Transverse cracks occurred most often in fibers which were free to move in the fabric structure and which suffered only gentle abrasion and surface bruising. In general, Clegg (6) found that the filling yarns were protected by the warp yarns; damage was primarily confined to breaks along transverse cracks. The warp yarns, though

more vulnerable to abrasion, evaded intense abrasive action because the fibers were mobile.

Abraded cotton fabrics studied by deGrury et al. (8) were stained with a modification of Simon's stain. The dyes used were Pontamine Sky Blue 6 BX and Pontamine Fast Orange 6 RN. The damaged areas stained orange and the undamaged areas stained blue. The technique is based on the differential adsorption rates of two dyes of different molecular size and shape. The accessibility of the mechanically disturbed cotton to the relatively large molecules of Pontamine Fast Orange 6 RN is an indication of the lateral separation of the original cellulose within the fiber. The lateral bonding of longitudinally oriented structures is weak within the fiber. These bonds are of low energy, probably hydrogen bonds. Transverse stresses produce a break more readily across the fiber than a break along the fiber axis.

Fabrics exposed to flex abrasion were stained, and microscopic examination of the fibers revealed: longitudinal splitting of the fiber; fragmentation and fraying of broken fibers; mashing or bruising; and clean, sharp breaks. Fiber mashing was usually accompanied by the accumulation of masses and clumps of detritus. Observable damage after flat abrasion included: snagged and cut fiber surfaces; excessive mashing; and deep lateral cuts in the sides of the fibers.

Isings (14) has done considerable research on the effect of stress and deformation on the structure of the cotton fiber. Though he used torsion and stretching as sources of stress, microscopic examination of the damaged fibers revealed cracks and wrinkles similar to those

observed in abraded fibers.

Douglas (9) studied damaged abraded fibers using photomicrographs. Cotton, Dacron polyester, Orlon acrylic, and nylon fabrics were abraded using an Accelerotor. Fibers were mounted and photographed using a trinocular microscope and a 35 mm photomicrographic camera. The damage the photomicrographs revealed included: ragged ends; surface damage; fibrillation; gouges and cuts; split fibers; hairiness; transverse cracks (especially the nylon); and swollen areas (also the nylon). The type of liner used in the Accelerotor appeared to affect the extent of damage to the fibers. The longer synthetic fibers were displaced less readily than the shorter cotton fibers. The abrasion had a plucking effect on both the yarn and the fabric which caused the fiber ends to be pulled away and a gradual loss of yarn cohesion was noted.

Wagner (26) also studied longitudinal sections of damaged fibers using a similar method of photomicrography. She abraded cotton and nylon fabrics at twelve levels using the Schiefer Abrader. The amount of pressure and the number of revolutions varied for each level. Three photomicrographs were taken at each level. Damage noted on the cotton fibers included: fragmentation; mashed ends; fibrillation; chewed fiber surfaces; surface cutting; transverse ridges; and accumulation of detritus. Damage increased in intensity as pressure and number of revolutions was increased.

Cross sections. Some work has also been reported on methods of staining cellulosic fibers, particularly viscose rayon, to detect certain defects in the fibers or to differentiate between the skin and core

of the fiber. Jolliff (15) used a two step dye bath consisting of Aniline Gentian Violet dye and Gram's iodine to study viscose rayon. He found that spun-in inhomogeneities could be detected as a result of the use of this particular stain. Any damage to the filament which penetrated to a depth equivalent to the skin thickness was readily distinguishable. Kato (17) used Azine Brilliant Blue to stain cross sections of viscose rayon to differentiate between the skin and core of the fibers. The same dye was applied to cotton fibers and provided an adequate stain for microscopic examination. The core of mercerized cotton could readily be differentiated from the skin. Kato (18) also developed a staining technique using Procion Black HGS to differentiate the skin and core of viscose rayon fibers. The cross sections were stained after embedding. The skin of the fibers was completely stained, but the core remained relatively unstained.

Difficulty had also been encountered in examining the cortical section of wool fibers stained prior to embedding. Snyman (25) found that by embedding wool fibers in butyl methacrylate, cutting cross sections on a sliding microtome, and then dyeing the sections for a short period of time with Methylene Blue, excellent differentiation between the cortical sections of wool could be achieved.

A combination of two dyes in which the dye solutions act as the mounting medium has been used by Smith (22). The dyes consist of a water solution of Methylene Blue and an alcohol solution of Sudan III. Though this technique was applied to natural and synthetic fiber cross sections, Smith cited certain limitations. The final color of the section may be

influenced by the thickness of the section and the presence of compounding ingredients. This limits the effectiveness of the method as an analytical tool. The dye also affects water-soluble or water-sensitive materials. Smith (22) found that cellulose swelled as much as 20 per cent. The dyes were washed off but the optical image was poor.

More recently Wahrenbrock (27) completed a study using photomicrographs to evaluate unstained and stained cross sections cut from the cotton and nylon fabrics abraded by Wagner (28). The cotton was stained with Congo Red. The fibers were photographed using a trinocular microscope and a 35 mm photomicrographic camera. The resulting photomicrographs indicated that much work still needs to be done in this area. The cotton fibers swelled, and streaks were frequently observed. The staining did not permit observations that indicated how damage had occurred. Good pictures were difficult to obtain using the high power objective because of the variation in the height of the fibers and the degree of precision required in focusing. Damage was most notable at the highest levels of abrasion. Wahrenbrock suggested that if staining could be done after mounting of the cross sections the resulting photomicrographs might be more readily analyzed. She also suggested utilizing a two-color stain which would provide for greater differentiation between the damaged and undamaged areas of the fibers.

By using a variety of staining techniques, it is hoped that this study can evaluate fabric breakdown more effectively. A more thorough study can be made by using colored photomicrographs and increasing the levels of abrasion.

CHAPTER III

METHOD OF PROCEDURE

The fabric utilized in this study was a one-hundred per cent cotton that was used in the North Central Regional Project NC-68. The Kansas Agricultural Experiment Station was one of the participating stations in the NC-68 project. The fabric was a plain weave with a two-ply yarn in the warp direction and a single ply yarn in the filling direction. The cotton fabric had a thread count of fifty-six in the warp direction and forty-nine in the filling direction.

The fabric, as originally prepared for the NC-68 project, was divided into five blocks numbered I, II, III, IV, and V. Each block was divided into six areas labeled A, B, C, D, E, and F. Each area was divided into sixty-six five inch square specimens (Appendix A). Assignment of the abrasion level and the type of testing to be done after abrasion for each specimen was determined by using IBM randomized sheets prepared by the NC-68 statistician. For this particular study, the NC-68 specimens designated for weight and thickness measurements were used to cut specimens for staining and embedding.

A coding system was established to designate the block and area from which each specimen was selected, the level each specimen was abraded, and the staining treatment each specimen received. The specimens were coded using a laundry marking pen. The following symbols were used in coding the specimens:

Block I = I	Abrasion level = 0, 1, 2, 3, 4, 5, 6
Block II = II	Warp ↑
Block III = III	Filling —→
Block IV = IV	Unstained = No mark
Block V = V	Stained with Congo Red = R
Area A = A	Stained with Pontamine Sky Blue 6 BX and Pontamine Fast Orange 6 RN = P
Area C = C	
Area D = D	Linda = L
Area F = F	

For example, I-C-l-↑-R-L was a specimen from Block I, Area C, abrasion level 1, ↑ warp direction, and stained with Congo Red. The "L" was included to distinguish the specimens from those in the NC-68 project.

The cotton specimens for abrading were cut from the five inch square specimens using a circular die 3.8146 inches in diameter. The specimens were abraded under standard conditions (70°F. ± 2 and 65% R.H. ± 2). A Schiefer Abrader was used with a spring steel abradant. All the specimens were mounted with a template using a 1.5 inch plastic disc as the presser foot in order to insure equal tension on each specimen. The NC-68 specimens had been abraded at nine levels, each level varying from the others in the amount of pressure applied and the number of revolutions. The levels varied from a light pressure, one pound, and short cycle (50 revolutions) to a heavy pressure, five pounds, and a long cycle (1,000 revolutions). From these nine levels, six levels were selected for examination (Appendix B) as best representative of changes that occurred with increased pressure and number

of revolutions. The unabraded specimens, level 0, served as a control.

The specimens for staining and embedding were cut from the 1.5 inch circular abraded portion of the NC-68 specimens. Cross sectional examination included both the warp and filling specimens at each level. Three warp and three filling specimens of the unabraded and abraded cotton at each level were stained with Congo Red; an equal number of specimens was stained with Pontamine Sky Blue 6 BX and Pontamine Fast Orange 6 RN. The same number of specimens was left unstained.

The method recommended by Clegg (7) for dyeing with Congo Red was used except the specimens were wet out in distilled water and blotted between filter paper before staining. The wet out cotton specimens were immersed in an eleven per cent solution of sodium hydroxide. The solution was shaken and allowed to stand for five minutes. The specimens were washed rapidly in distilled water and then placed in a concentrated (two per cent) solution of Congo Red. The dye bath was shaken at intervals for six minutes. The specimens were rinsed in distilled water until no more dye came off; the dyed specimens were then immersed in an eighteen per cent solution of sodium hydroxide, removed, and allowed to dry.

The technique recommended by deGrury et al. (8) for staining specimens with Pontamine Sky Blue 6 BX and Pontamine Fast Orange 6 RN was followed except that the dyes were applied to the fabric prior to cross-sectioning. The specimens were soaked in a five per cent solution of sodium hydroxide for five minutes and rinsed in distilled water. The specimens were stained with a one per cent solution of Pontamine Sky

Blue 6 BX, dried at 70°C., and rinsed in distilled water six times. The specimens were blotted between filter paper and immersed in a one per cent solution of Pontamine Fast Orange 6 RN. The specimens were dried, rinsed four more times in distilled water, and dried again.

Both unstained and stained specimens were embedded. The specimens were stapled to 1.5 by 0.625 inch cardboard frames and labeled with a laundry marking pen. Each specimen was placed in a number eleven gelatin capsule and dried in an oven for thirty minutes at 45°C. A Lucite solution was used for embedding. The solution was prepared by mixing together 300 ml. of methyl methacrylate (with inhibitor), 170 ml. of di(n) butyl phthalate, and 2.5 gms. of benzoyl peroxide. The capsules were filled to within one-eighth of an inch of the top with the Lucite solution, tightly covered with tops, and placed in a 45°C. oven for twenty-four to forty-eight hours, or until the solution hardened. In order to prevent bubble formation in the Lucite solution as the capsules hardened, a periodic check of the oven temperature should be made so the oven does not get too warm. The capsules were removed from the oven and placed in running warm water for thirty minutes. When the gelatin was completely dissolved, the Lucite molds were removed and dried. A raised portion with vertical sides about one-eighth inch by one-fourth inch was shaped around the top of the embedded fabric with an exacto knife. Six slices were cut from each specimen at an angle of 45° with a thickness of fourteen microns using an American Optical Company sliding microtome. If white streaks appear in the Lucite portion of the cross section, it is evident that the knife edge in the microtome needs

to be sharpened. The cross sections were mounted on slides in immersion oil and covered with a cover glass.

The microscopic analysis was done using an American Optical Company Series 4 Microstar Trinocular microscope. The unstained and stained cross sections were studied using the ten and forty-three power objectives, the ten-power eyepieces, and substage illumination. The ten power objective was used to study the damage to the total cross section and the interlacing yarn. The forty-three power objective was used to study damage to the individual fibers. After studying the six cross sections on the slide, one photomicrograph was made at each magnification. The photomicrographs were taken using a 35 mm camera which was attached to the vertical tube of the trinocular body of the microscope. Kodacolor X-Negative film was used. Color film was used to enable a more thorough evaluation of the damage to the unstained and stained cross sections. A blue filter was used to give a clear picture and to cut down on glare.

A comparison of the photomicrographs of unstained and stained cross sections of unabraded and abraded cotton fabrics was made for each level. Photomicrographs of the unstained cross sections were compared with the photomicrographs of the stained cross sections to determine if staining contributed to the researcher's ability to detect damage caused by abrasion. Photomicrographs of the cross sections stained with Congo Red were compared with the cross sections stained with Pontamine Sky Blue 6 BX and Pontamine Fast Orange 6 RN to determine if the dye and the technique used in staining influenced the ability of

the researcher to adequately determine the extent of damage to the fabric and the fibers.

CHAPTER IV

DISCUSSION

Photomicrographs of the cross sections of the unstained and stained cotton fabric which had been abraded at six levels varying in amount of pressure and number of revolutions were made using the ten power objective and the forty-three power objective. The photomicrographs were compared to evaluate the extent of abrasive damage at the different levels and to evaluate the effect of staining in assessing damage. Specifically, the photomicrographs were compared to evaluate the effectiveness of two different stains.

The cotton fabric specimens readily absorbed the Congo Red dye; this is seen in the photomicrographs in Plates II, V, VIII, and XI. For the most part, the damaged areas stained a deep red while the undamaged areas stained light red or pink. The cotton fabric stained with the Pontamine Sky Blue 6 BK and Pontamine Fast Orange 6 RN dyes readily absorbed the blue dye. The cut edges of the abraded fabric absorbed the orange dye, indicating that damaged cotton fibers do have an affinity for this particular dyestuff. However, the photomicrographs shown in Plates III, VI, IX, and XII indicated that very little of the orange dye was absorbed by the fibers in the abraded area of the specimens. Close examination of the photomicrographs indicated that some orange dye had been absorbed by the fibers at the outer edges of the fiber bundles (Plate IX, Fig. 4). The orange dye appeared to have been more readily absorbed by those fibers that had been pulled out of the yarn

structure. The extent of abrasive damage may not have been sufficient to cause the fibers to absorb a substantial quantity of the orange dye for the dye to be seen in a photomicrograph.

The photomicrographs indicated that there was a change in the size of the fibers as a result of staining. This could be seen quite clearly by comparing the photomicrographs of the stained cross sections with the photomicrographs of the unstained cross sections at the higher magnification. This was an expected result because the stained fibers were soaked in caustic soda prior to immersion in the dye bath; and it is well-known that a caustic soda solution produces a swelling effect in cotton fibers. The fibers stained with Congo Red appeared to have swollen to a greater extent than those fibers stained with the Pontamine dyes. The caustic soda solution used in the Congo Red dyeing technique was more concentrated than the solution used in the Pontamine two-dye bath. The Congo Red dyeing technique also employed two applications of the caustic soda solution. These differences in the dyeing methods undoubtedly influenced the extent of swelling of the cotton fiber.

I. TEN POWER OBJECTIVE

Warp. The cross section of the unstained, unabrased cotton fabric revealed a generally coherent yarn structure and compact fiber bundles with just a few loose fibers noticeable at the edge of the yarn (Plate I, Fig. 1). The appearance of the yarn at level 1 (Plate I, Fig. 2) varied slightly from the unabrased yarn. More loose fibers had been separated from the fiber bundle. At levels 2 and 3 (Plate I, Figs. 3

EXPLANATION OF PLATE I

Photomicrographs of Unstained Cross Sections
from the Warp of the Cotton Fabric
Using the Ten Power Objective
(magnification 25 times)

Fig. 1	Unabraded
Fig. 2	Abrasion level 1
Fig. 3	Abrasion level 2
Fig. 4	Abrasion level 3
Fig. 5	Abrasion level 4
Fig. 6	Abrasion level 5
Fig. 7	Abrasion level 6

PLATE I



Fig. 1



Fig. 2



Fig. 3



Fig. 4



Fig. 5



Fig. 6



Fig. 7

and 4) the yarn structure had become less compact; fibers at the edges of the yarn began to separate from the yarn. As the fibers separated from the fiber bundles, the fibers tended to assume a more elongated shape, and many more loose fibers were seen. At level 4 (Plate I, Fig. 5) there were many sheared fibers along the edge of the yarn. The size and compactness of the yarn diminished considerably at level 5 (Plate I, Fig. 6). Long fibers had separated completely from the yarn, and the fiber ends appeared to be fibrillating. At level 6 (Plate I, Fig. 7) a complete breakdown of the yarn structure was evident. Many long loose fibers could be seen. At one point in the yarn the fibers had been completely destroyed.

The cross section of the unabraded cotton warp yarn stained with Congo Red dye revealed a very coherent, even yarn structure (Plate II, Fig. 1). The bundles of fibers were quite round in shape. Levels 1 and 2 (Plate II, Figs. 2 and 3) showed little change in the compactness of the yarn; however, the fibers within the fiber bundles had begun to separate rather distinctly into two bundles. A few short loose fibers were noticed. At levels 3 and 4 (Plate II, Figs. 4 and 5) the yarn had become less compact as the fibers along the entire length of the yarn began to pull apart. Several of the fiber bundles had completely separated, and short, loose fibers were evident. The fiber bundle was no longer round, but had become more oval or, in some instances, almost rectangular in configuration. At level 5 (Plate II, Fig. 6) the yarn had become extremely thin in several places as fibers had been sheared off and worn away. The yarn resembled a mass of loosely connected long

EXPLANATION OF PLATE II

Photomicrographs of Cross Sections from the Warp
of the Cotton Fabric Stained with Congo Red

Using the Ten Power Objective

(magnification 25 times)

- | | |
|--------|------------------|
| Fig. 1 | Unabraded |
| Fig. 2 | Abrasion level 1 |
| Fig. 3 | Abrasion level 2 |
| Fig. 4 | Abrasion level 3 |
| Fig. 5 | Abrasion level 4 |
| Fig. 6 | Abrasion level 5 |
| Fig. 7 | Abrasion level 6 |

PLATE II



Fig. 1

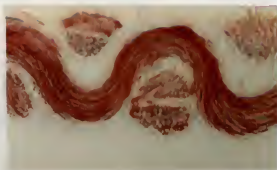


Fig. 2



Fig. 3



Fig. 4



Fig. 5



Fig. 6



Fig. 7

fibers, rather than a continuous, coherent fiber strand. The yarn structure at level 6 (Plate II, Fig. 7) had completely separated into two distinct strands. Along the length of the yarn broken or sheared fibers were evident. Many fibers had pulled loose from the fiber bundles, and these fibers were becoming elongated. Some fibrillation could be seen.

The cross section of the unabraded cotton warp yarn stained with Pontamine Sky Blue 6 EX and Pontamine Fast Orange 6 RN also revealed a very compact yarn structure and round fiber bundles (Plate III, Fig. 1). At level 1 (Plate III, Fig. 2) the yarn structure was still relatively compact with just a few loose fibers apparent. The fibers within the fiber bundles had begun to separate at level 2 (Plate III, Fig. 3), and a large number of short, loose fibers was seen. At one point in the yarn a long fiber had been pulled away at the edge of the yarn. Levels 3 and 4 (Plate III, Figs. 4 and 5) showed little change in the structure. The yarn appeared to be more bulky and the fibers had begun to separate from the fiber bundles. At level 5 (Plate III, Fig. 6), however, the yarn had been damaged considerably. At several places along the length of the yarn fibers had been sheared off and pulled away from the yarn structure. The fibers in the outer regions of the fiber bundles were elongated. Some fibrillation was detected. The shape of the fiber bundle had become more oval as the fibers within the bundle moved outward. At level 6 (Plate III, Fig. 7) the yarn had deteriorated further. The yarn had become very thin in several places as many long fibers had been broken away from the yarn structure. The fiber bundles

EXPLANATION OF PLATE III

Photomicrographs of Cross Sections from the Warp
of the Cotton Fabric Stained with Pontamine Sky

Blue 6 BX and Pontamine Fast Orange 6 RN

Using the Ten Power Objective

(magnification 25 times)

- | | |
|--------|------------------|
| Fig. 1 | Unabraded |
| Fig. 2 | Abrasion level 1 |
| Fig. 3 | Abrasion level 2 |
| Fig. 4 | Abrasion level 3 |
| Fig. 5 | Abrasion level 4 |
| Fig. 6 | Abrasion level 5 |
| Fig. 7 | Abrasion level 6 |

PLATE III



Fig. 1



Fig. 2



Fig. 3



Fig. 4



Fig. 5



Fig. 6



Fig. 7

were oval or elliptical in shape with the fibers spread out considerably.

Filling. The cross sections of the unabraded and unstained cotton filling yarn (Plate IV, Fig. 1) revealed a compact yarn structure with just a few loose fibers at the outer edges of the fiber bundles. At levels 1 and 2 (Plate IV, Figs. 2 and 3) the yarn appeared fuller as more long fibers had been pulled from the yarn. However, the yarn had become very thin at level 3 (Plate IV, Fig. 4). Broken and sheared fibers were evident. The fibers at the outer edges of the fiber bundles had been pulled slightly away from the bundles and appeared elongated. At level 4 (Plate IV, Fig. 5) the yarn was thin, and there were many loose fibers surrounding both the yarn and the fiber bundles. The yarn structure had deteriorated even further at level 5 (Plate IV, Fig. 6). Many loose and broken fibers were evident, and the yarn had lost its coherent structure. The fibers within the fiber bundles were elongated and spread out in a fan-like effect. At level 6 (Plate IV, Fig. 7) the yarn structure was maintained by one fiber as other fibers had been pulled away or sheared off.

The cross section of the unabraded cotton filling yarn stained with the Congo Red dye revealed a relatively compact yarn and elliptically shaped fiber bundles (Plate V, Fig. 1). At level 1 (Plate V, Fig. 2) the fibers in the yarn had begun to separate. Several fibers had been sheared off and there was some evidence of fibrillation. The fiber bundle had begun to separate, too. This yarn separation continued at level 2 (Plate V, Fig. 3), to the extent that many loose fibers

EXPLANATION OF PLATE IV

Photomicrographs of Unstained Cross Sections
from the Filling of the Cotton Fabric
Using the Ten Power Objective
(magnification 25 times)

- | | |
|--------|------------------|
| Fig. 1 | Unabraded |
| Fig. 2 | Abrasion level 1 |
| Fig. 3 | Abrasion level 2 |
| Fig. 4 | Abrasion level 3 |
| Fig. 5 | Abrasion level 4 |
| Fig. 6 | Abrasion level 5 |
| Fig. 7 | Abrasion level 6 |

PLATE IV



Fig. 1



Fig. 2



Fig. 3



Fig. 4



Fig. 5



Fig. 6



Fig. 7

EXPLANATION OF PLATE V

Photomicrographs of Cross Sections from the Filling
of the Cotton Fabric Stained with Congo Red

Using the Ten Power Objective

(magnification 25 times)

- | | |
|--------|------------------|
| Fig. 1 | Unabraded |
| Fig. 2 | Abrasion level 1 |
| Fig. 3 | Abrasion level 2 |
| Fig. 4 | Abrasion level 3 |
| Fig. 5 | Abrasion level 4 |
| Fig. 6 | Abrasion level 5 |
| Fig. 7 | Abrasion level 6 |

PLATE V



Fig. 1



Fig. 2



Fig. 3



Fig. 4



Fig. 5



Fig. 6



Fig. 7

could be seen. The fibers within the fiber bundles had spread apart and appeared quite elongated in shape. Level 3 (Plate V, Fig. 4) showed only a slight difference from level 2. Yarn separation continued, and at level 4 (Plate V, Fig. 5) a clean break had occurred in the yarn structure. The fibers continued to move farther apart. At level 5 (Plate V, Fig. 6) the yarn could no longer be considered compact. Many broken and sheared fibers were evident. The fibers within the fiber bundles were spread apart and were misshapen. The yarn at level 6 (Plate V, Fig. 7) appeared to be almost twice as bulky as the unabraded yarn. The yarn had separated into two fiber strands; at several points along each strand, the fibers had been broken. At other places, the strands were very thin as fibers had pulled loose from the structure. The fiber bundles were distorted, and the fibers were elongated in shape.

The cross section of the unabraded cotton filling yarn stained with Pontamine Sky Blue 6 EX and Pontamine Fast Orange 6 RN also indicated a relatively compact yarn and elliptically shaped fiber bundles (Plate VI, Fig. 1). Level 1 (Plate VI, Fig. 2) showed very little change. At level 2 (Plate VI, Fig. 3), however, the fibers within the fiber bundles had begun to separate and several short fibers had been pulled from the yarn. At level 3 (Plate VI, Fig. 4) many loose fibers were evident, and the fibers at the edges of the fiber bundles appeared elongated in shape. At one point in the yarn structure, all but a few fibers had worn away; the yarn was very thin. At levels 4 and 5 (Plate VI, Figs. 5 and 6) the fiber bundles showed a definite lack of

EXPLANATION OF PLATE VI

Photomicrographs of Cross Sections from the Filling
of the Cotton Fabric Stained with Pontamine Sky
Blue 6 EX and Pontamine Fast Orange 6 RN

Using the Ten Power Objective
(magnification 25 times)

- | | |
|--------|------------------|
| Fig. 1 | Unabraded |
| Fig. 2 | Abrasion level 1 |
| Fig. 3 | Abrasion level 2 |
| Fig. 4 | Abrasion level 3 |
| Fig. 5 | Abrasion level 4 |
| Fig. 6 | Abrasion level 5 |
| Fig. 7 | Abrasion level 6 |

PLATE VI



Fig. 1



Fig. 2



Fig. 3

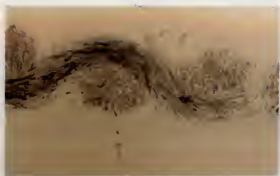


Fig. 4



Fig. 5



Fig. 6



Fig. 7

coherence; the fibers were spread out in a fan-like effect. The fibers within the yarn had separated slightly, and several long fibers had been sheared off. The yarn was an unorganized mass of broken fibers. At level 6 (Plate VI, Fig. 7) the yarn structure had broken down completely. The fibers still in tact in the yarn were spread apart, giving the yarn a very bulky appearance. Many broken fibers were evident. The fiber bundles were distorted, and the fibers within the bundles were spread apart.

The use of a stain did aid in identifying the damaged areas of the yarn. Staining highlighted the individual fibers and gave a more definite outline to all portions of the photomicrographs. Some differences between the stains were noted. The Congo Red dye, perhaps because of the intensity of the color, produced a photomicrograph in which the yarn and the individual fibers could be easily identified; damage could be readily ascertained. The Pontamine dyes, while clearly producing a more examinable photomicrograph than those photomicrographs of the unstained fabric, did not give the contrast produced by the Congo Red dye. The background color approximated that of the fabric in many instances. Damage, however, was visible, though not as a result of the damaged fiber's affinity for the orange dye.

II. FORTY-THREE POWER OBJECTIVE

Warp. The photomicrograph of the unabraded, unstained cotton fabric (Plate VII, Fig. 1) revealed quite clearly the compactness of the fiber bundles mentioned throughout the above discussion. The

EXPLANATION OF PLATE VII

Photomicrographs of Unstained Cross Sections
from the Warp of the Cotton Fabric
Using the Forty-three Power Objective
(magnification 107.5 times)

- | | |
|--------|------------------|
| Fig. 1 | Unabraded |
| Fig. 2 | Abrasion level 1 |
| Fig. 3 | Abrasion level 2 |
| Fig. 4 | Abrasion level 3 |
| Fig. 5 | Abrasion level 4 |
| Fig. 6 | Abrasion level 5 |
| Fig. 7 | Abrasion level 6 |

PLATE VII



Fig. 1



Fig. 2



Fig. 3



Fig. 4



Fig. 5



Fig. 6



Fig. 7

fibers were close together and were generally the same shape. At level 1 (Plate VII, Fig. 2) there appeared to be some separation of the fibers, but the change was slight. Slight separation of the fibers into two groups was noticed at level 2 (Plate VII, Fig. 3). The bundle was no longer compact as several fibers appeared to have been pulled out of the bundle. These fibers were elongated in shape, and slight damage to the cell wall was indicated. At level 3 (Plate VII, Fig. 4) more fibers had separated from the fiber bundle. Those fibers at the edge of the bundle which had not separated completely from the bundle appeared to be square or rectangular in shape. The fibers had spread apart even further at level 4 (Plate VII, Fig. 5). Several sheared fibers could be seen; partial removal of the cell wall was also evident. At level 5 (Plate VII, Fig. 6) more fibers had moved away from the main portion of the fiber bundle. Partial disintegration of the cell wall was detected in the fibers at the edge of the fiber bundle. Level 6 (Plate VII, Fig. 7) indicated more damaged fibers which had breaks or portions of the cell wall removed.

The photomicrographs of the unabraded cotton warp yarn stained with Congo Red (Plate VIII, Fig. 1) revealed again a very compact fiber bundle with no visible damage to the individual fibers. At level 1 (Plate VIII, Fig. 2) the fibers had started to separate slightly. At levels 2 and 3 (Plate VIII, Figs. 3 and 4) the fibers had separated into two distinct groups, and the fibers along this line of separation showed some damage to the cell walls. Several of the fibers which had been pulled out of the bundle seemed transparent and were laid across

EXPLANATION OF PLATE VIII

Photomicrographs of Cross Sections from the Warp
of the Cotton Fabric Stained with Congo Red
Using the Forty-three Power Objective
(magnification 107.5 times)

- | | |
|--------|------------------|
| Fig. 1 | Unabraded |
| Fig. 2 | Abrasion level 1 |
| Fig. 3 | Abrasion level 2 |
| Fig. 4 | Abrasion level 3 |
| Fig. 5 | Abrasion level 4 |
| Fig. 6 | Abrasion level 5 |
| Fig. 7 | Abrasion level 6 |

PLATE VIII



Fig. 1



Fig. 2



Fig. 3



Fig. 4



Fig. 5



Fig. 6



Fig. 7

the surface of the bundle. Those fibers at the edges of the bundles appeared misshapen and almost transparent. Breaks in the cell walls of several fibers were evident. At levels 4 and 5 (Plate VIII, Figs. 5 and 6) more fibers had been pulled from the edges of the bundles. Within the bundle holes were evident where fibers had apparently been plucked from the center. These plucked fibers were elongated, and partial breakdown of the cell wall was evident. At level 6 (Plate VIII, Fig. 7) continued separation of the fiber bundles was seen. At the edge of the bundle a large number of fibers had been removed. These fibers were elongated, and the cell walls had been partially removed.

The cross section of the unabraded cotton warp yarn stained with Pontamine Sky Blue 6 BX and Pontamine Fast Orange 6 RN also revealed a very round, compact bundle of fibers (Plate IX, Fig. 1). At level 1 (Plate IX, Fig. 2) fibers near the edges of the bundle had begun to separate from the bundle. The extent of separation increased considerably at level 2 (Plate IX, Fig. 3) as the fibers spread out in a random fashion. Slight damage to the cell walls was apparent, particularly in those fibers at the outer portion of the bundle. At level 3 (Plate IX, Fig. 4) many of the fibers assumed an elongated shape, and cell wall damage was evident, especially at the ends of the fibers. Several fibers with breaks in the cell wall were noted at levels 4 and 5 (Plate IX, Figs. 5 and 6), and fiber separation continued. At level 6 (Plate IX, Fig. 7) groups of fibers had separated from the bundle.

Filling. The photomicrographs of the unabraded filling yarn of the unstained cotton fabric showed a very elongated mass or bundle of

EXPLANATION OF PLATE IX

Photomicrographs of Cross Sections from the Warp
of the Cotton Fabric Stained with Pontamine Sky

Blue 6 BX and Pontamine Fast Orange 6 RN

Using the Forty-three Power Objective

(magnification 107.5 times)

- | | |
|--------|------------------|
| Fig. 1 | Unabraded |
| Fig. 2 | Abrasion level 1 |
| Fig. 3 | Abrasion level 2 |
| Fig. 4 | Abrasion level 3 |
| Fig. 5 | Abrasion level 4 |
| Fig. 6 | Abrasion level 5 |
| Fig. 7 | Abrasion level 6 |

PLATE IX



Fig. 1



Fig. 2



Fig. 3



Fig. 4



Fig. 5



Fig. 6



Fig. 7

compact fibers (Plate X, Fig. 1). At level 1 (Plate X, Fig. 2) slight separation of the fibers had occurred, but no other damage was noticeable. The fibers had begun to move farther apart at level 2 (Plate X, Fig. 3), and at level 3 (Plate X, Fig. 4) several fibers appeared to have breaks in the cell wall. Several fibers had also been pulled completely away from the bundle. At levels 4 and 5 (Plate X, Figs. 5 and 6) an increased number of fibers had separated from the bundle. Some of these fibers appeared to have been sheared into two parts. At level 6 (Plate X, Fig. 7) there was widespread separation of the fibers. The bundle had lost its original coherency and many loose fibers were evident. Cell wall deterioration was more prominent.

The photomicrographs of the unabraded cotton filling yarn stained with Congo Red dye indicated a compact bundle of fibers, the total mass being somewhat elliptical in shape (Plate XI, Fig. 1). At level 1 (Plate XI, Fig. 2) the fibers had begun to separate; two slits in the fiber bundle were apparent. At the edge fibers had also started to pull away. These fibers at the edges appeared to be transparent, and there was some indication of damage to the cell walls. Damaged fibers were also seen at level 2 (Plate XI, Fig. 3), particularly at the edges of the fiber bundle. At level 3 (Plate XI, Fig. 4) many of the fibers appeared almost square or rectangular in shape. Separation continued as the fibers spread farther apart. The fibers at level 4 (Plate XI, Fig. 5) indicated a tendency to separate into two distinct bundles. The fibers along this separating line appeared elongated and transparent. At level 5 (Plate XI, Fig. 6) widespread separation of the fibers

EXPLANATION OF PLATE X

Photomicrographs of Unstained Cross Sections
from the Filling of the Cotton Fabric
Using the Forty-three Power Objective
(magnification 107.5 times)

- | | |
|--------|------------------|
| Fig. 1 | Unabraded |
| Fig. 2 | Abrasion level 1 |
| Fig. 3 | Abrasion level 2 |
| Fig. 4 | Abrasion level 3 |
| Fig. 5 | Abrasion level 4 |
| Fig. 6 | Abrasion level 5 |
| Fig. 7 | Abrasion level 6 |

PLATE X



Fig. 1



Fig. 2



Fig. 3



Fig. 4



Fig. 5



Fig. 6



Fig. 7

EXPLANATION OF PLATE XI

Photomicrographs of Cross Sections from the Filling
of the Cotton Fabric Stained with Congo Red
Using the Forty-three Power Objective
(magnification 107.5 times)

- | | |
|--------|------------------|
| Fig. 1 | Unabraded |
| Fig. 2 | Abrasion level 1 |
| Fig. 3 | Abrasion level 2 |
| Fig. 4 | Abrasion level 3 |
| Fig. 5 | Abrasion level 4 |
| Fig. 6 | Abrasion level 5 |
| Fig. 7 | Abrasion level 6 |

PLATE XI



Fig. 1



Fig. 2



Fig. 3



Fig. 4



Fig. 5



Fig. 6



Fig. 7

had occurred. Several of the fibers looked like bubbles. Partial removal of the cell wall was evident at several points. The fibers at level 6 (Plate XI, Fig. 7) had spread out in a fan-like effect with those at the edge of the bundle showing evidence of fragmentation and cell wall damage.

The photomicrographs of the unabraded cotton filling yarn stained with Pontamine Sky Blue 6 BX and Pontamine Fast Orange 6 RN revealed a compact fiber bundle (Plate XII, Fig. 1). At levels 1 and 2 (Plate XII, Figs. 2 and 3) several long fibers had been pulled away from the bundle, and the transparent effect seen at the end of these fibers appeared to indicate a break in the cell wall. At level 3 (Plate XII, Fig. 4), however, a large clump of fibers had been pulled from the bundle, again appearing transparent along a portion of the fiber length. Other fibers within the bundle had separated. Fiber separation was readily apparent at levels 4 and 5 (Plate XII, Figs. 5 and 6) as the bundle seemed to lose all cohesiveness. Several fibers appeared transparent and elongated. Many long loose fibers could be seen, and cell wall deterioration was evident. At level 6 (Plate XII, Fig. 7) the fibers had spread far apart, and those at the edge of the bundle were fragmented and elongated in shape.

The use of a stain did aid in identifying the damaged areas of the cotton fabric, particularly at this higher magnification. Staining produced a clear image of the fiber so that individual fibers were easily recognized. The Congo Red dye produced a vivid contrast of color. Those areas of the fibers that were damaged to a greater extent

EXPLANATION OF PLATE XII

Photomicrographs of Cross Sections from the Filling
of the Cotton Fabric Stained with Pontamine Sky

Blue 6 BX and Pontamine Fast Orange 6 RN

Using the Forty-three Power Objective

(magnification 107.5 times)

- | | |
|--------|------------------|
| Fig. 1 | Unabraded |
| Fig. 2 | Abrasion level 1 |
| Fig. 3 | Abrasion level 2 |
| Fig. 4 | Abrasion level 3 |
| Fig. 5 | Abrasion level 4 |
| Fig. 6 | Abrasion level 5 |
| Fig. 7 | Abrasion level 6 |

PLATE XII



Fig. 1



Fig. 2



Fig. 3



Fig. 4



Fig. 5



Fig. 6



Fig. 7

did stain a deeper red color (Plate XI, Fig. 6). The Pontamine Sky Blue 6 BX and Pontamine Fast Orange 6 RN dyes did stain the fabric sufficiently so that fibers could be easily identified and examined. The color contrast between the fibers and the background was very slight, however; this tended to produce a photomicrograph with fibers outlined and detailed but not with the same distinctness that was produced by use of the Congo Red dye. Even at this higher magnification only slight traces of the Pontamine Fast Orange 6 RN dye could be detected (Plate XII, Fig. 4). Apparently the damage to the fibers was not sufficient to cause larger amounts of this dyestuff to be absorbed by the fibers.

CHAPTER V

SUMMARY AND RECOMMENDATIONS

This study was designed to evaluate the effect of two different stains in assessing the extent of damage to a cotton fabric abraded at levels which varied in the amount of pressure applied and the number of revolutions. The fabric utilized was a one-hundred per cent cotton that was used in the North Central Regional Project NC-68. The fabric specimens had been abraded using the Schiefer Abrader equipped with a spring steel abradant. Cross-sectional examination included both the warp and filling specimens at each abrasion level. Three warp and three filling specimens of the cotton at each level were stained with Congo Red; an equal number of specimens was stained with Pontamine Sky Blue 6 BX and Pontamine Fast Orange 6 RN. The same number of specimens was left unstained.

Both the unstained and stained specimens were embedded in a Lucite solution. After hardening the capsules were shaped with an exacto knife, and cross sections were cut using an American Optical Company Sliding Microtome. Six cross sections were cut at an angle of 45° and a thickness of fourteen microns from each capsule. The cross sections were mounted on slides in immersion oil.

The stained and unstained cross sections were studied using an American Optical Company Series 4 Microstar Trinocular microscope. A 35 mm camera attached to the vertical tube of the trinocular body of the microscope was used to take photomicrographs. Kodacolor X-negative

color film was used to take the photomicrographs. Photomicrographs were taken using both the ten power objective and the forty-three power objective. A blue filter enabled a clearer picture to be taken. One photomicrograph that was felt to be representative of the six cross sections on the slide was taken at each magnification.

The Congo Red dye and the Pontamine Sky Blue 6 BX - Pontamine Fast Orange 6 RN dyes were both used to differentiate between the undamaged and the damaged areas of the cotton fabric. Both stains were useful in ascertaining the extent of damage to the fibers. The Congo Red dye produced a vivid color that afforded great contrast between the background and the fibers. Individual fibers could be readily studied, particularly at the high magnification. For the most part, damaged fibers were highlighted by a deeper red color.

The Pontamine Sky Blue 6 BX and Pontamine Fast Orange 6 RN dyes produced little contrast between the background and the fibers; however, the stain did tend to give the fibers an outlined effect, and individual fibers could be studied and evaluated. Damaged fibers did not appear to absorb the orange dye; only traces of the dye could be detected even at the high magnification. The dye, therefore, did not distinguish between the undamaged and damaged portions of the fibers. However, a certain amount of damage could be detected. Perhaps this dyestuff has affinity only for fibers that are severely damaged.

The photomicrographs revealed a very compact yarn structure in both the warp and filling directions. Many loose fibers were seen at levels 1 and 2. Fiber separation had occurred to a great extent at

these levels in the filling yarn. At level 3 the warp yarn appeared split along its entire length into two fiber strands. The filling yarn was quite thin in several places as broken fibers apparently had been pulled from the yarn structure. Large clumps of fibers had been pulled out of the fiber bundles, and the first indication of cell wall damage was seen. The first evidence of cell wall damage to the warp yarn was seen at level 4. Long loose fibers had been sheared from the yarn. These loose fibers, particularly in the filling direction, were transparent and elongated in shape. The warp yarn had become very thin at level 5, and large holes appeared in the fiber bundles where fibers had apparently been plucked from the yarn. The filling yarn had completely deteriorated in several places. By level 6 the warp yarn had also broken down, and cell wall damage was readily apparent, especially in those fibers at the edge of the fiber bundles.

Since this study was only exploratory, an attempt was made to find satisfactory methods to study fiber breakdown occurring as a result of flat abrasion. It would be interesting to use Congo Red and the Pontamine dyes to stain cotton fabrics that were subjected to other types of abrasion. A study of staining techniques used in biological and pathological laboratories might reveal other dyes that could prove useful in staining fibers. It would be interesting to study a larger sample of specimens, perhaps using fabric taken from worn textile garments. Experimentation with the exposure time of the film, especially when using the high power objective, is recommended. It is also suggested that in further studies of this nature the color film be

purchased all in one lot to avoid the differences in the color of the finished photomicrographs that can be seen in some of the photomicrographs discussed above.

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APPENDICES

APPENDIX A

SAMPLING PLAN REPRESENTING ONE OF THE SIX AREAS
WITHIN EACH OF THE FIVE BLOCKS*

1	2	3	4	5	6
7	8	9	10	11	12
13	14	15	16	17	18
19	20	21	22	23	24
25	26	27	28	29	30
31	32	33	34	35	36
37	38	39	40	41	42
43	44	45	46	47	48
49	50	51	52	53	54
55	56	57	58	59	60
61	62	63	64	65	66

* In accordance with the experimental design of Project 636,
Kansas Agricultural Experiment Station, North Central Regional Project
NC-68.

APPENDIX B

ABRASION LEVELS*

Level	Pounds of Pressure	Revolutions
0	Unabraded	
1	1	300
2	3	100
3	3	500
4	5	300
5	5	750
6	5	1000

* Selected from the experimental design of Project 636, Kansas Agricultural Experiment Station, North Central Regional Project NC-68.

EVALUATION OF UNSTAINED AND STAINED COTTON FABRIC BEFORE
AND AFTER ABRASION USING COLORED PHOTOMICROGRAPHS

by

LINDA MARGARET CARLIN

B. S., Drexel Institute of Technology, 1965

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Clothing, Textiles, and Interior Design

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1968

The purpose of this study was to compare the extent of damage to a 100 per cent cotton fabric abraded on a Schiefer Abrader at varying levels by using colored photomicrographs of unstained and stained cross sections of the fabric. It was designed to observe differences between the unstained and stained cross sections and to differentiate between the undamaged and the damaged areas of the fabric.

A portion of the cotton was stained with Congo Red dye; another portion was stained with a Pontamine Sky Blue 6 BX/Pontamine Fast Orange 6 RN dye. The remaining fabric was left unstained. The specimens were embedded in Lucite solution, and cross sections were mounted in immersion oil. Ten and forty-three power objectives, ten-power eyepieces, and substage illumination were used to study the unstained and stained cross sections from each abrasion level. Representative cross sections of each were photographed using Kodacolor X-negative film.

The unstained fibers were difficult to evaluate for specific abrasive damage. The Congo Red dye showed damaged fibers highlighted by a deep red color. The Pontamine Sky Blue 6 BX/Pontamine Fast Orange 6 RN dye did not distinguish between the undamaged and damaged portions of the fibers as much as was anticipated.

The photomicrographs revealed a very compact yarn structure in both the warp and filling directions. Abrasion resulted in fiber separation of filling yarn as broken fibers pulled from the yarn, and cell wall damage was evident. Long, loose fibers appeared transparent and elongated in shape as they were sheared from yarns. Abrasion caused the warp yarn to become very thin as large groups of fibers were

plucked from the fiber bundles. At the highest abrasion level yarns were completely destroyed, and cell wall damage could be readily seen.